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# New signatures for a light stop at LEP2 in SUSY models with spontaneously broken R-parity

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## Abstract

In a class of supersymmetric models with R-parity breaking the lightest stop can have new decay modes into third generation fermions,  $\tilde{t}_1 \rightarrow b + \tau$ . We show that this decay may be dominant or at least comparable to the ordinary R-parity conserving mode  $\tilde{t}_1 \rightarrow c + \tilde{\chi}_1^0$ , where  $\tilde{\chi}_1^0$  denotes the lightest neutralino. The new R-parity violating decay modes could provide new signatures for stop production at LEP.

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# 1 Introduction

So far most searches for supersymmetric particles have so far been performed within the framework of the ***Minimal Supersymmetric Standard Model (MSSM)*** [1]. Although the MSSM is by far the most well studied realization of supersymmetry, there is considerable theoretical and phenomenological interest in studying possible implications of alternative scenarios [2], in which R-parity is broken. Indeed, neither gauge invariance nor supersymmetry requires the conservation of R-parity. The violation of R-parity could arise explicitly [3] as a residual effect of some larger unified theory [4], or spontaneously, through nonzero vacuum expectation values (VEV's) for scalar neutrinos [5]. In realistic spontaneous R-parity breaking models [6, 7, 8, 9] the scale of R-parity violation lies around the TeV scale. Its effects can therefore be large enough to be experimentally observable. Moreover, these models are fully consistent with astrophysics and cosmology [2]. In either case the supersymmetric (SUSY) particles need not be produced only in pairs, and the lightest of them could decay.

There are two generic cases of spontaneous R-parity breaking models to consider. If lepton number is part of the gauge symmetry there is an additional gauge boson which gets mass via the Higgs mechanism, and there is no physical Goldstone boson [9]. In this model the lightest SUSY particle (LSP) is in general a neutralino which decays mostly into visible states, therefore breaking R-parity. The main decay modes are three-body decays such as

$$\tilde{\chi}_1^0 \rightarrow f\bar{f}\nu, \quad (1)$$

where  $f$  denotes a charged fermion. Its invisible decay modes are in the channel

$$\tilde{\chi}_1^0 \rightarrow 3\nu. \quad (2)$$

Alternatively, if spontaneous R-parity violation occurs in the absence of any additional gauge symmetry, it leads to the existence of a physical massless Nambu-Goldstone boson, called majoron ( $J$ ). Thus in this case ***the lightest SUSY particle is the majoron*** which is massless and therefore stable<sup>7</sup>. As a consequence the lightest neutralino  $\tilde{\chi}_1^0$  may decay invisibly as

$$\tilde{\chi}_1^0 \rightarrow \nu + J, \quad (3)$$

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<sup>7</sup>The majoron may have a small mass due to explicit breaking effects at the Planck scale. In this case it may decay into neutrinos and photons. However, the time scales are only of cosmological interest and do not change the signal expected in laboratory experiments [10].

where the majoron is mainly a singlet [6, 7]. This last decay conserves R-parity since the majoron has a large R-odd singlet sneutrino component.

In this paper we focus on the decay modes of the lightest top squark in models where supersymmetry is realized with spontaneous R-parity violation. In such models the lightest stop could even be the lightest supersymmetric particle and be produced at LEP. Indeed present  $e^+e^-$  collider data [11] as well as  $p\bar{p}$  collider data [12] do not preclude this possibility.

In supersymmetric models with spontaneous breaking of R-parity or in models, where this violation is parametrized explicitly through a bilinear superpotential term of the type  $\ell H_u$  [13], the stop can have new decay modes such as

$$\tilde{t}_1 \rightarrow b + \tau \quad (4)$$

due to mixing between charged leptons and charginos. In this paper we show that this decay may be dominant or at least comparable to the ordinary R-parity conserving mode

$$\tilde{t}_1 \rightarrow c + \tilde{\chi}_1^0, \quad (5)$$

where  $\tilde{\chi}_1^0$  denotes the lightest neutralino.

## 2 Lepton-Gaugino-Higgsino Mixing

The basic tools in our subsequent discussion are the chargino and neutralino mass matrices. The chargino mass matrix may be written as [6]

$$\begin{array}{c|ccc} & e_j^+ & \tilde{H}_u^+ & -i\tilde{W}^+ \\ \hline e_i & h_{eij}v_d & -h_{\nu ij}v_{Rj} & \sqrt{2}g_2v_{Li} \\ \tilde{H}_d^- & -h_{eij}v_{Li} & \mu & \sqrt{2}g_2v_d \\ -i\tilde{W}^- & 0 & \sqrt{2}g_2v_u & M_2 \end{array} \quad (6)$$

Its diagonalization requires two unitary matrices  $U$  and  $V$

$$\chi_i^+ = V_{ij}\psi_j^+ \quad (7)$$

$$\chi_i^- = U_{ij}\psi_j^-, \quad (8)$$

where the indices  $i$  and  $j$  run from 1 to 5 and  $\psi_j^+ = (e_1^+, e_2^+, e_3^+, \tilde{H}_u^+, -i\tilde{W}^+)$  and  $\psi_j^- = (e_1^-, e_2^-, e_3^-, \tilde{H}_d^-, -i\tilde{W}^-)$ .

While the details of the neutralino mass matrix are rather model dependent, for our purposes it will be sufficient to use the following effective form given by [6]

$$\begin{array}{c|ccccc} & \nu_i & \tilde{H}_u & \tilde{H}_d & -i\tilde{W}_3 & -i\tilde{B} \\ \hline \nu_i & 0 & h_{\nu ij}v_{Rj} & 0 & g_2v_{Li} & -g_1v_{Li} \\ \tilde{H}_u & h_{\nu ij}v_{Rj} & 0 & -\mu & -g_2v_u & g_1v_u \\ \tilde{H}_d & 0 & -\mu & 0 & g_2v_d & -g_1v_d \\ -i\tilde{W}_3 & g_2v_{Li} & -g_2v_u & g_2v_d & M_2 & 0 \\ -i\tilde{B} & -g_1v_{Li} & g_1v_u & -g_1v_d & 0 & M_1 \end{array} \quad (9)$$

This matrix is diagonalised by a  $7 \times 7$  unitary matrix  $N$ ,

$$\chi_i^0 = N_{ij}\psi_j^0, \quad (10)$$

where  $\psi_j^0 = (\nu_i, \tilde{H}_u, \tilde{H}_d, -i\tilde{W}_3, -i\tilde{B})$ , with  $\nu_i$  denoting the three weak-eigenstate neutrinos.

In the above equations  $v_u$  and  $v_d$  are the VEV's responsible for the breaking of the electroweak symmetry and the generation of fermion masses, where the combination  $v^2 = v_u^2 + v_d^2$  is fixed by the  $W, Z$  masses.  $v_R$  is the VEV mostly responsible for the spontaneous violation of R-parity<sup>8</sup>. Moreover,  $M_{1,2}$  denote the supersymmetry breaking gaugino mass parameters and  $g_{1,2}$  are the  $SU(2) \otimes U(1)$  gauge couplings divided by  $\sqrt{2}$ , and we assume the canonical relation  $M_1/M_2 = \frac{5}{3}\tan^2\theta_W$ . Note that the effective Higgsino mixing parameter  $\mu$  may be given in some models as  $\mu = h_0 \langle \rangle$ , where  $\langle \rangle$  is the VEV of an appropriate singlet scalar.

Most of our subsequent analysis will be general enough to cover a wide class of  $SU(2) \otimes U(1)$  models with spontaneously broken R-parity, such as those of ref. [6, 7], as well as models where the majoron is absent due to an enlarged gauge structure [9]. Many of the phenomenological features relevant for the LEP studies discussed here already emerge in an effective model, where the violation of R-parity is introduced explicitly through a bilinear superpotential term of the type  $\ell H_u$  [13]. In this case the combination  $h_\nu v_R$  is replaced by a mass parameter  $\epsilon$ .

Typical values of interest for LEP2 for the SUSY parameters  $\mu, M_2$ , and the

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<sup>8</sup>There is also a small seed of R-parity breaking in the doublet sector,  $v_L = \langle \tilde{\nu}_{L\tau} \rangle$ , whose magnitude is related to the Yukawa coupling  $h_\nu$ . Since this vanishes as  $h_\nu \rightarrow 0$ , we can naturally obey the limits from stellar energy loss [14]

parameters  $h_{\nu i,3}$  lie in the range given by

$$\begin{aligned} -1000 \text{ GeV} &\leq \mu \leq 1000 \text{ GeV} & 40 \text{ GeV} &\leq M_2 \leq 200 \text{ GeV} \\ 10^{-10} &\leq h_{\nu 13}, h_{\nu 23} \leq 10^{-1} & 10^{-5} &\leq h_{\nu 33} \leq 10^{-1} \end{aligned} \tag{11}$$

while the expectation values can be chosen as

$$\begin{aligned} v_L \equiv v_{L3} &= 100 \text{ MeV} & v_{L1} = v_{L2} &= 0 \\ 50 \text{ GeV} &\leq v_R \equiv v_{R3} \leq 1000 \text{ GeV} & v_{R1} = v_{R2} &= 0 \end{aligned} \tag{12}$$

with  $1 \lesssim \tan \beta = \frac{v_u}{v_d} \lesssim 40$ .

There are restrictions on these parameters that follow from searches for SUSY particles at LEP [11] and the TEVATRON [12]. In addition, we take into account the constraints from neutrino physics and weak interactions phenomenology [15], which are more characteristic of R-parity breaking models. These are important, as they exclude many parameter choices that are otherwise allowed by the constraints from the collider data, while the converse is not true. Due to these constraints R-parity violation effects manifest themselves mainly in the third generation as expressed in eq. (12). In order to evaluate the masses and couplings of charginos and neutralinos we have performed a sampling of parameters in our model which are allowed by all constraints above.

One finds that the R-parity conserving couplings for the lightest neutralino  $\tilde{\chi}_1^0$  and the lightest chargino  $\tilde{\chi}_1^\pm$  are of the same order as those in the MSSM. The R-parity violating chargino couplings may reach a few percent or so for chargino masses accessible at LEP [15, 16]. These couplings will induce a mixing between the charginos and the tau lepton, leading to the R-parity violating decay in eq. (4). The corresponding decay width will be calculated below.

### 3 Decays of the Top Squark

As we saw in the previous section, R-parity breaking effects should occur mainly in the third generation, due to the mixing of the charged leptons with the charginos. As a result the decay mode  $\tilde{t}_1 \rightarrow b + \tau$  is possible. In the following we assume  $m_{\tilde{t}_1} < m_b + m_{\tilde{\chi}_1^+}$ . In this case the most important R-parity conserving stop decay at LEP2 is  $\tilde{t}_1 \rightarrow c + \tilde{\chi}_1^0$  [17]. Now the question arises whether the branching ratios of the decays into  $b\tau$  and  $c\tilde{\chi}_1^0$  are of comparable size. As we will

show  $\tilde{t}_1 \rightarrow b + \tau$  can be equally or even more important than  $\tilde{t}_1 \rightarrow c + \tilde{\chi}_1^0$ . We have also taken into account the decay  $\tilde{t}_1 \rightarrow c + \tilde{\chi}_2^0$ , which is also possible in a small region of parameter space. In the alternative case  $m_{\tilde{t}_1} > m_b + m_{\tilde{\chi}_1^+}$  the decay mode  $\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^+$  would clearly dominate the decays (4) and (5). A detailed discussion of all R-parity conserving stop decays at LEP2 is given in [18].

The decay  $\tilde{t}_1 \rightarrow c + \tilde{\chi}_1^0$  is only possible in higher order (see Fig. 1). As shown in [19] the dominant contribution is due to  $\tilde{t}_1 \rightarrow \tilde{c}_L \rightarrow c \tilde{\chi}_1^0$ . This can be parametrized by the following squark mass squared matrix in the  $(\tilde{t}_L, \tilde{t}_R, \tilde{c}_L)$  basis:

$$M^2 = \begin{pmatrix} M_{\tilde{t}_L}^2 & a_t m_t & {}_L \\ (a_t m_t)^* & M_{\tilde{t}_R}^2 & {}_R \\ {}_L^* & {}_R^* & M_{\tilde{c}_L}^2 \end{pmatrix}. \quad (13)$$

Explicit expressions for  $M_{\tilde{t}_L}^2, M_{\tilde{t}_R}^2, a_t m_t, M_{\tilde{c}_L}^2$  and  ${}_L, {}_R$  can be found in ref. [19]. Quite generally, flavour changing mass terms are induced in supergravity models assuming unification and evolution according to the renormalization group equations [20]. The light stop eigenstate can therefore be written as:

$$\tilde{t}_1 = c_1 \tilde{t}_L + c_2 \tilde{t}_R + \delta \tilde{c}_L. \quad (14)$$

Estimates for  $\delta$  were given in [19]. These are, however, very model dependent as pointed out in [21]. Nevertheless a value  $\delta \sim \sqrt{\frac{L,R}{M_q^2}}$  may be regarded as typical. For our present phenomenological discussion we take a very strong  $\tilde{t}\tilde{c}$  mixing,  $\delta \sim O(0.1)$ . To be specific, we shall take  $\delta = 0.1$ . Note that this is a conservative assumption, i.e. should  $\delta$  be smaller, the relative importance of our novel decay eq. (4) would be further enhanced.

The decay widths for (4) and (5) are:

$$\begin{aligned} (\tilde{t}_1 \rightarrow b + \tau) &= \frac{g^2}{16\pi m_{\tilde{t}_1}^3} \sqrt{(m_{\tilde{t}_1}^2 - m_b^2 - m_\tau^2)^2 - 4m_b^2 m_\tau^2} \\ &\quad \times ((l^2 + k^2)(m_{\tilde{t}_1}^2 - m_b^2 - m_\tau^2) - 4lkm_b m_\tau) \end{aligned} \quad (15)$$

$$(\tilde{t}_1 \rightarrow c + \tilde{\chi}_i^0) = \frac{g^2}{16\pi m_{\tilde{t}_1}^3} |\delta|^2 f_i^2 (m_{\tilde{t}_1}^2 - m_{\tilde{\chi}_i^0}^2)^2 \quad (16)$$

where

$$l = \frac{m_t}{\sqrt{2}m_W \sin \beta} V_{34} c_2 K_{tb} - V_{35} (c_1 K_{tb} + \delta K_{cb}), \quad k = \frac{m_b K_{tb}}{\sqrt{2}m_W \cos \beta} U_{34} c_1 \quad (17)$$

$$f_1 = -\frac{\sqrt{2}}{6} (\tan \theta_W N_{47} + 3N_{46}), \quad f_2 = -\frac{\sqrt{2}}{6} (\tan \theta_W N_{57} + 3N_{56}) \quad (18)$$

Here  $V_{34}$ ,  $U_{34}$  ( $V_{35}$ ) denote the amount of tau-Higgsino (tau-gaugino) mixing (see eq. (6) and eq. (8)) and  $K_{tb} = 0.999$ ,  $K_{cb} = 0.04$  are the corresponding CKM matrix elements [22].

For a dominantly Higgsino-like neutralino [23] (small  $N_{i6}$  and  $N_{i7}$ ) the R-parity conserving decay is induced by the charm Yukawa coupling and is therefore suppressed (see eq. (16) and eq. (18)). As a result, the branching ratio of the R-parity violating  $b\tau$  mode will be enhanced.

In our present numerical analysis we have fixed  $m_{\tilde{t}_1} = 80$  GeV,  $c_1 = 0.5$ ,  $v_R = 100$  GeV,  $v_L = 0.1$  GeV and  $h_{\nu 33} = 0.03$ . We have varied the other parameters in the range given in eq. (12) and eq. (11). As already mentioned, we have taken into account all bounds from the LEP experiments as well as neutrino physics [15]<sup>9</sup>. In Fig. 2 we show the maximum value of the branching ratio for  $\tilde{t}_1 \rightarrow b + \tau$  in per cent as a function of the lightest neutralino mass  $m_{\tilde{\chi}_1^0}$  in the range  $1 \leq \tan \beta \leq 40$ . One can see that  $\text{BR}(\tilde{t}_1 \rightarrow b + \tau)$  can easily reach 80 % for neutralino masses of 50 GeV. There are a few points, not shown in Fig. 2, which lie **above** the "maximum curve" even for relatively small neutralino masses. They correspond to "fine-tuned" situations where  $f_1$  almost vanishes due to a cancellation between the terms in eq. (18) for small  $\tan \beta$  values.

Particularly interesting is the dependence on  $\tan \beta$ , which can be seen in Fig. 3. The most characteristic feature is the existence of a strong correlation between the branching ratio for the  $b\tau$  stop decay mode and  $\tan \beta$ , apart from a small region in parameter space characterized by small  $\tan \beta$  where  $f_1$  vanishes and the R-parity conserving decay is suppressed<sup>10</sup>. One can clearly see that most points with a large branching ratio of  $\tilde{t}_1 \rightarrow b + \tau$  have a large  $\tan \beta$ . Note that in the framework of the MSSM with radiative electroweak breaking such large  $\tan \beta$  models have been advocated [25]. The trend towards large  $\tan \beta$  can be understood as being due to the influence of the large bottom Yukawa coupling (see eq. (17)). It is also interesting to note that for large  $\tan \beta$  there is a sizeable minimum value for the R-parity breaking decay branching ratio.

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<sup>9</sup>Note that the MSSM LEP limits on neutralino masses do not hold in broken R-parity models. For a recent discussion see ref. [24].

<sup>10</sup>These points correspond precisely to those we have eliminated from Fig. 2 as mentioned above.

## 4 Discussion

We have shown that in a class of supersymmetric models with R-parity breaking the stop can have new decay modes to third generation fermions such as  $\tilde{t}_1 \rightarrow b + \tau$ . For stop masses accessible at LEP2 and smaller than the chargino masses the branching ratio for the R-parity violating decay mode  $\tilde{t}_1 \rightarrow b + \tau$  can be comparable or even larger than the R-parity conserving mode  $\tilde{t}_1 \rightarrow c + \tilde{\chi}_1^0$ . Note also that quite generally the R-parity breaking decay branching ratio could be increased through a larger value of  $h_{\nu 33}$ , a smaller value of  $\delta$ , a larger value of the Higgsino content of the neutralino, or any combination of these. In fact, if R-parity is violated the lightest stop  $\tilde{t}_1$  can be lighter than the lightest neutralino  $\tilde{\chi}_1^0$  leading to a  $\sim 100\%$  branching ratio into the  $\tilde{t}_1 \rightarrow b + \tau$  decay mode. Finally, one should not forget that even in the case when  $\tilde{t}_1 \rightarrow c + \tilde{\chi}_1^0$  is the main stop decay mode, the resulting signature will be different from that expected in the MSSM, because the lightest neutralino will decay. From eq. (1), (2), (3) the expected modes are:  $\tilde{\chi}_1^0 \rightarrow J + \nu, 3\nu, l^- + l^+ + \nu, \tau^\pm + l^\mp + \nu, q + \bar{q} + \nu, q + \bar{q}' + \nu$ . While the first two decays give the same signature as in the MSSM, which is a c-jet and missing momentum, the others give rise to events with additional leptons or quarks. In order to identify the corresponding signals in detail, one would have to take into account all possible neutralino decay channels, and evaluate the corresponding detection efficiencies and standard model backgrounds in a dedicated Monte Carlo simulation.

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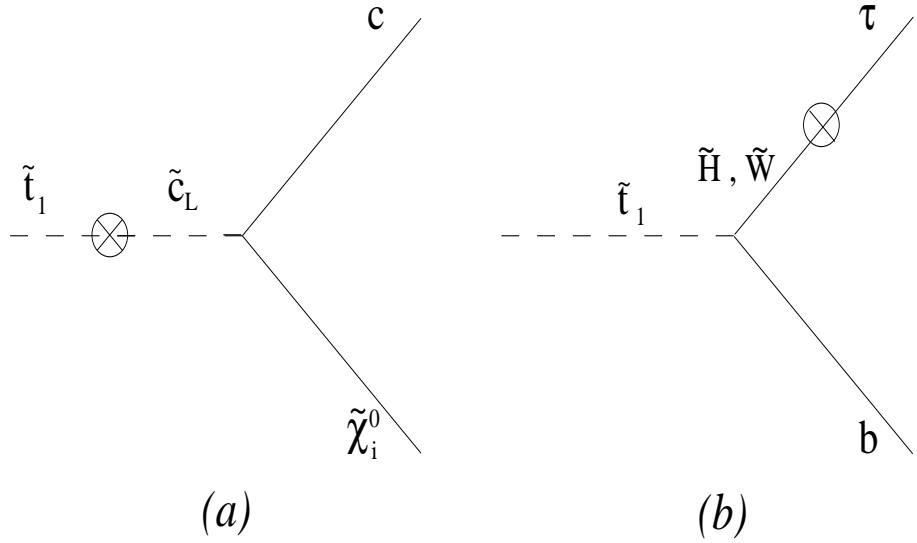


Figure 1: Feynman diagrams leading to the standard R-parity conserving decay (a) and the new R-parity violating stop decay (b).

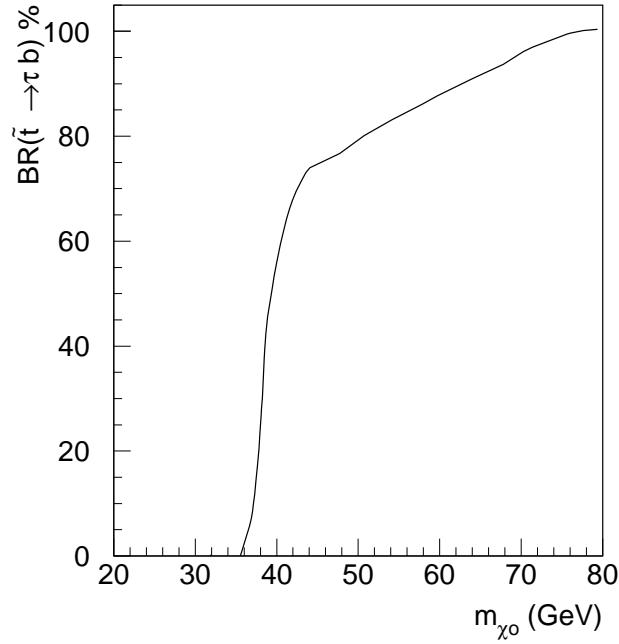


Figure 2: Barring unlikely small  $f_1$  values as discussed in the text, the curve displays the maximum values for the branching ratio for  $\tilde{t}_1 \rightarrow b + \tau$  in per cent as a function of the lightest neutralino mass  $m_{\tilde{\chi}_i^0}$ . We have taken  $m_{\tilde{t}_1} = 80$  GeV,  $c_1 = 0.5$ ,  $\delta = 0.1$ ,  $v_R = 100$  GeV,  $v_L = 0.1$  GeV and  $h_{\nu 33} = 0.03$  and varied the remaining parameters as explained in the text

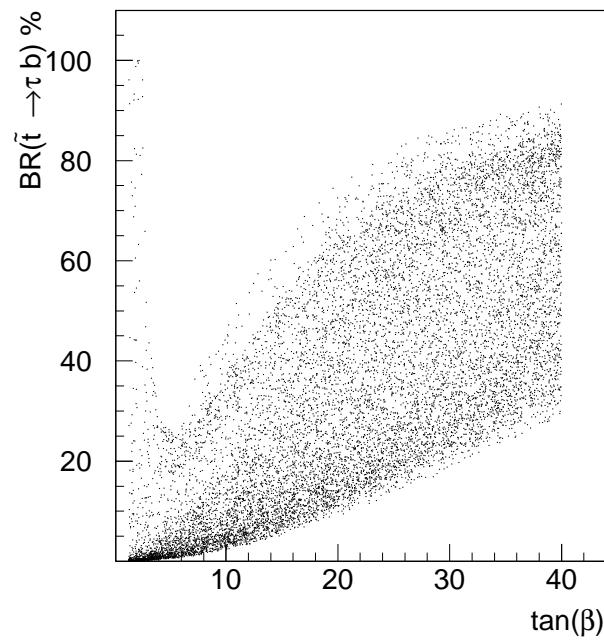


Figure 3: Scatter-plot for values of branching ratio for  $\tilde{t}_1 \rightarrow b + \tau$  in per cent as a function of  $\tan \beta$  for  $55 < m_{\chi_1} < 60$  GeV. All parameters are chosen as in figure 2.